Department of Communications and Networking

Comnet: Annual Report 2011

Aalto University

SCIENCE + TECHNOLOGY

ANNUAL REPORT

Aalto University publication series
SCIENCE + **TECHNOLOGY** 14/2012

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Aalto University
School of Electrical Engineering
Department of Communications and Networking

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DEPARTMENT OF COMMUNICATIONS AND NETWORKING
SCHOOL OF ELECTRICAL ENGINEERING
AALTO UNIVERSITY

ANNUAL REPORT 2011

CONTENTS

INTRODUCTION

COMNET IN BRIEF

The Department of Communications and Networking (Comnet) is a multi-disciplinary unit of research and higher education covering communications and networking technology, networking business, and human aspects of communication and communications technology. In its area, Comnet is the largest unit in Finland. Comnet develops communications, information and teletraffic theory and conducts fundamental and applied experimental research in communications and networking technology. In shaping the Internet technology, Comnet is a significant force internationally.

REVIEW OF 2011

DEPARTMENT HEAD'S REPORT

I started as the head of the department in September 2011. I inherited the department in good shape from my predecessor, Professor Raimo Kantola. The department was formed as a result of the merger of the 60-plus-year-old Networking laboratory and the 40-plus-year-old Communications Laboratory. Raimo and our previous coordinator, Mrs. Arja Hänninen, did an excellent job in managing the merger and defining new processes for the department. We have a friendly and encouraging working atmosphere and, as a result of the merger, the interactions between the research groups have been increasing.

The steering group developed the research strategy of the department based on the results of the Research Assessment Exercise conducted within Aalto in 2009. We defined our research philosophy, the vision of the department, the drivers of research in our area, the grand challenges, and the focus areas as well as the fundamental themes or basic areas of competence that we must possess and develop further. In our research strategy we named the following grand challenges:

(1) carbon neutral networking,

(2) instant wireless Internet, and

(3) scaling the Internet for 1000 devices per user.

During 2010 and 2011 we have been able to launch new projects in these areas, and we have made several strategic actions to improve the quality of our research. For instance, we have managed to recruit more than 10 post-doctoral researchers to the department, and significant investments in laboratory equipment have also been made. The productivity of the department has been rising. The year 2011 was a record year in the number of doctoral dissertations for Comnet. Eight doctoral theses were defended by students of Comnet during 2011. Also, the number of publications increased from 2010 by 20%. This is a strong indication of the success of our strategy of focusing more on post-graduate education and research. It also indicates that many of the research groups at Comnet begin to reach maturity.

The department has also managed to increase its visibility in the international research community. Professor Brendan Mumey of the Montana State University stayed at the department as a visiting Aalto Fullbright professor from August 2011 until January 2012. Also, the Comnet professors Jörg Ott and Jukka Manner, jointly with Jussi Kangasharju from University of Helsinki, won the bidding competition of organizing SIGCOMM 2012 in Helsinki and have been actively organizing the event.

During 2010, Comnet started to implement an investment program into its research infrastructure. The program is planned to last for 3 years. The need for a significant upgrade of the research infrastructure is dictated by several factors. (1) Shifting to multi-antenna radios demands new measurement and simulation facilities. (2) Many data networks currently run on 10Gbit/s links requiring upgrades to data capturing and data network measurement devices. (3) Our student laboratories need major upgrading. (4) We also joined PlanetLab Europe and created a local research network allowing us to by-pass the production network of

the University. The research network is a generic facility that can be used in many research projects over the coming years. (5) We are also upgrading our own computing facilities to be used for simulations and computational science projects. (6) Finally, we are building an experimental data center for energy efficiency research. In all, we are planning to invest more than 1M€ into our research infra within the investment program. This is on top of the regular upgrades into the personal computers of our staff.

The year 2011 was the second year of Aalto University and the first year of Aalto School of Electrical Engineering (Aalto ELEC). The short-lived School of Science and Engineering, the successor of the TKK, was split into four schools. We got a new dean, Dr. Tuija Pulkkinen, who came from the Finnish Meteorological Institute in January. Establishing a new school has taken a lot of effort from the professors, and especially from the admin team.

To summarize, the year 2011 was a mix of management confusion due to introduction of new school with maturing of Comnet as a research unit with growing international recognition and growing output of doctoral degrees and publications.

June 13, 2012 Riku Jäntti

ADMINISTRATION

PERSONNEL

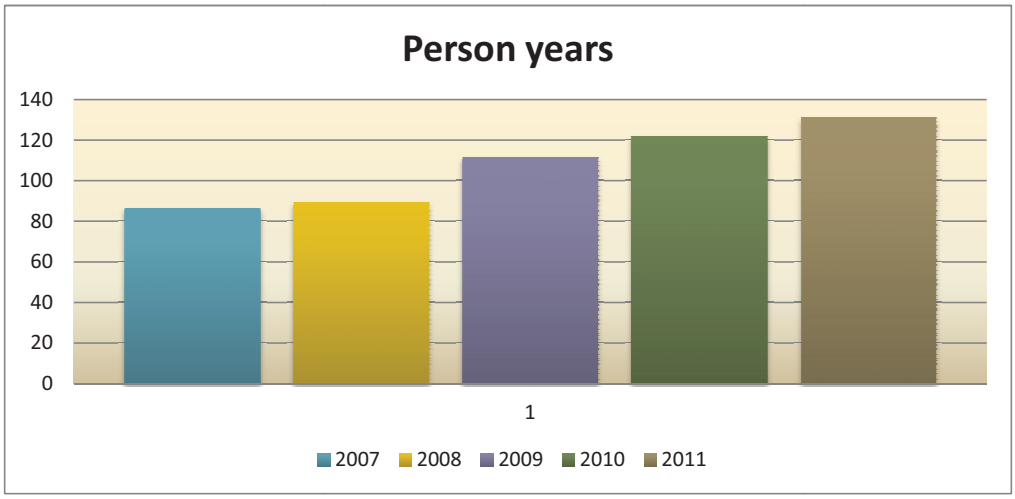

Figure 1: Development of the person years

Table 1: Personnel structure

Year	2007	2008	2009	2010	2011
Professors	7	9	9	9	9
Researchers	31	32	45	52,5	63
Research assistants	27	29	37	40	34
Grad schools	6	6	6	8,5	10
Teaching personnel	6	4	4	2	2
Part-time teachers	3	3	3	3	3,5
Technical services	3	3	3	3	5
Administration	3	3	4	4	4,5
Total	86	89	111	122	131

PROFESSORS

Riku Jäntti, Head of Department

Patric Östergård, Deputy Head of Department

Samuli Aalto

Heikki Hämmäinen

Jyri Hämäläinen

Raimo Kantola

Jukka Manner

Jörg Ott

Peter Reichl

Olav Tirkkonen

Professors Emeriti

Sven-Gustav Häggman

Kauko Rahko

Jorma Virtamo

IT SERVICES AND MEASUREMENT PLATFORMS

The ICT infrastructure of a department must support a variety of demands set by research and teaching. They create high competence requirements for the support staff and high expectations for the environment compared to a typical office. The needs of research and teaching cannot be met without

dedicated and skillful staff that is also able to give good support for normal office computing needs. Having a touch for the “normal” environment is important to keep connection with the reality of ICT organizations and demands set by those environments.

It was seen that department must maintain its high quality day-to-day operations in ICT support to provide the service the research groups need. This was strengthened by hiring two additional support persons, one part-time and one full-time, for the duration of the study leave of our long-time ICT support person. These additional resources have proven to be valuable.

Research activities in the department require in part significant processing power; some require large amounts of memory while some handle large data sets. To provide for these needs, a computational cluster as well as large storage capacity exceeding 50 TB is available for the researchers. Networking research and teaching needs also a large number of routers and other networking hardware as well as testing equipment. These devices are acquired in part directly by projects, partly from the common budget, and some are also received as donations from equipment vendors and network operators.

Besides IT support, the infrastructure of the department also includes measurement platforms for practical experiments. The focus is mostly on wireless communications, but we also need the capability for measuring coaxial cables and optical components. These resources were continuously upgraded also in 2011.

Our platform for RF measurements currently includes a wideband radio channel simulator, spectrum/signal analyzers, vector signal generators, vector analyzers, a time-domain reflectometer, and multi-channel oscilloscopes. This platform supports measurements with bandwidth up to 80 MHz, in frequency range up to 6 GHz. A software-defined radio platform (a cognitive radio system) is available to implement specialized wireless applications, including MIMO algorithms and protocols.

New optical communication measurement devices were acquired to replace outdated devices. For Ethernet and IP networks, the measurement capability for 10 Gbit/s Ethernet was improved with traffic generator and traffic capture cards. The student laboratory of networking technology received 21 Cisco routers for building an operator-scale learning environment.

At the end of 2011 the department was building two new research facilities: a radio communication research laboratory and a test data center. Research of modern radio communication systems and equipments needs also possibility of over-the-air measurements without unwanted interference from other radios. Thus, a sufficiently large RF-shielded and RF-anechoic environment is needed. An existing RF-shielded room has been modified for this purpose.

The constructing of another test facility, the test data center, moved forward in late 2011 when the public bidding for an advanced cooling system including heat recovery and re-use was completed. The data center cooling is expected to be operational in May 2012. This project is motivated by practical needs for larger test facilities but also as a platform of studying energy efficient data centers in co-operation with the departments of Electrical Engineering and Civil and Structural Engineering.

Comnet has a direct research network connection to FUNET. This has proven valuable in developing co-operation with other research institutes, including Nokia Lablet in Otaniemi, and experimenting with new technologies without endangering the integrity and security of the Aalto campus network.

As the research network increases in size, a large part of it is also used for teaching. A large network provides a real-world like environment for students to develop their skills and apply the knowledge they have acquired on lecture courses. Disciplines within the department are continuously integrated to provide full-scale learning environments for students and researchers.

FINANCIAL ISSUES

COSTS AND SOURCES OF FUNDING

Table 2: Development of costs 2008-2011

Costs	2008	2009	2010	2011
Personnel	3 828 932	4 835 007	5 580 000	6 087 658
Equipment	108 115	128 809	234 000	395 085
Rents	287 498	315 985	550 000	553 689
Other	702 306	1 360 880	910 000	930 711
Total	4 926 851	6 640 681	7 274 000	7 967 143
Change from previous year		35 %	10 %	10 %

Table 3: Development of funding 2008-2011

Source of Funding	2008	2009	2010	2011
Aalto funding	1 974 211	2 404 444	2 495 525	3 667 758
Academy of Finland	237 132	375 518	525 000	596 180
Tekes	1 128 833	1 798 586	2 443 000	2 060 502
Finnish companies	499 739	1 065 128	751 000	1 973 330
EC funding	428 311	312 312	401 000	654 016
Other funding	984 647	2 292 447	1 959 000	548 997
Internal funding (MIDE etc.)				289 079
Total	5 252 873	8 248 435	8 574 525	9 789 862

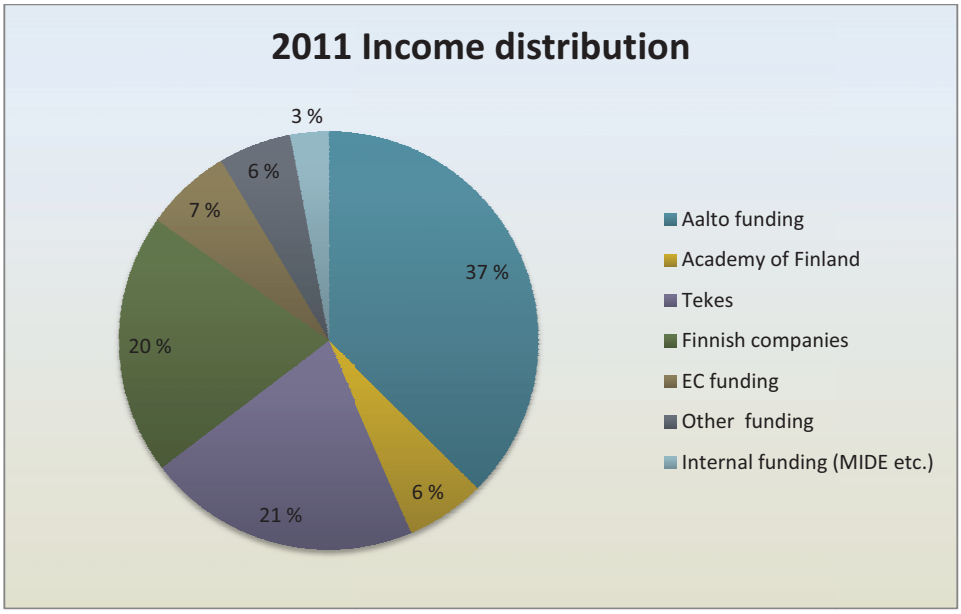

Figure 2: Sources of funding in 2011

SOCIAL IMPACT

Information and Communications Technology is an important exports industry for Finland. ICT is penetrating deeper and deeper all areas of economics and all types of services in the society. Advancement in the growth of productivity in the economy is largely attributed to the use of ICT. This makes the education we give highly relevant for the Finnish economy. The proportion of communications engineering sector among the 100 largest R&D companies in Finland was 77% in 2010. Even if Nokia's share is removed from the figures, the proportion is still 10%. The recruitment of ICT experts in the industry has grown annually about 2% but the growth has shifted from large companies to small and medium size companies.

The social impact can be measured in terms of competence and new knowledge that is produced and used by the economy. Practical measures are how well our graduates are employed and where and with whom we partner in research, as well as the volume of the collaborative research that we conduct.

The high societal impact was recognized as the strongest feature of Comnet in the Research Assessment Exercise by the international review board in 2009. We were graded 5/5 on this measure by the board.

Figure 3 shows that a number of our graduates are employed by the big ICT companies in Finland. At the same time it shows that the graduates spread out widely into the Finnish economy.

We collaborate with tens of Finnish and some foreign companies and organizations in Research projects some of which are organized as collaborative research and some are directly funded by the companies or organizations. We also have important role in helping governmental organizations to develop their networking infrastructure.

In Figure 4 we show the distribution of our research project partners.

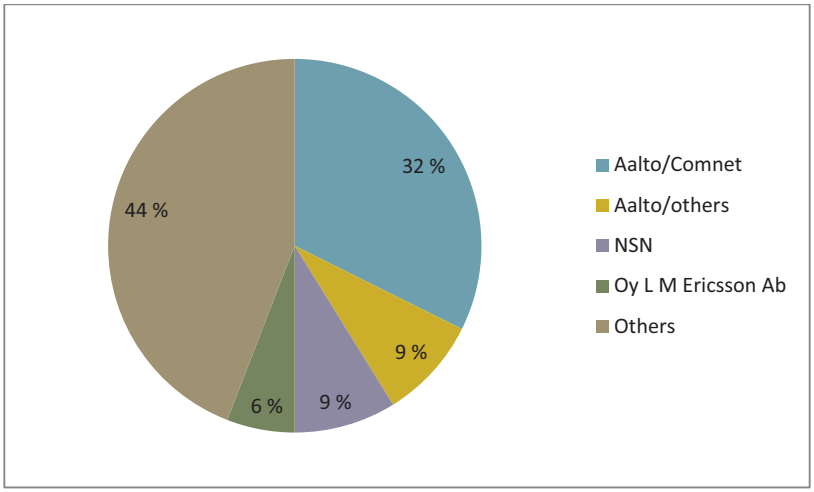

Figure 3: Employers of Master´s thesis students in 2011

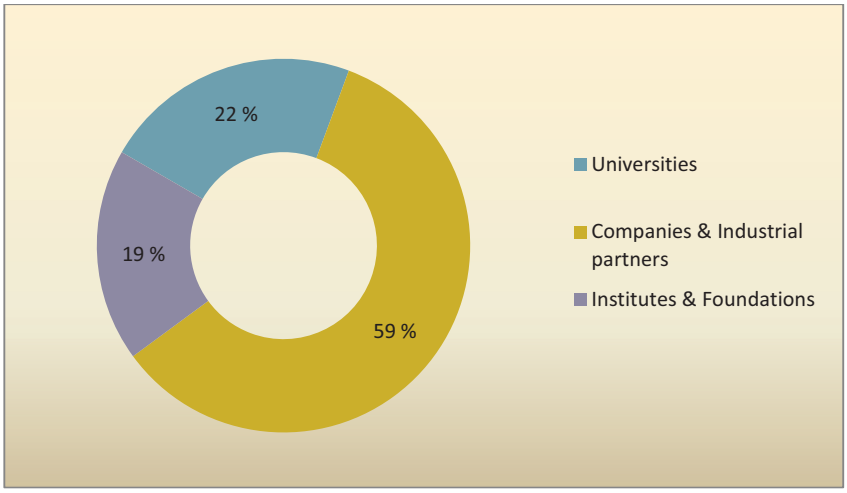

Figure 4: The cooperation – Comnet's partners in projects

TEACHING

Comnet provides mainly master's and doctoral level education, but we also have the main responsibility for the courses related to communications and networks in the B.Sc level Degree Programme in Communications Engineering for native students. Having started internationalization of the master's level education in 1999, our International Master's Programme in Communications is doing well, and the programme still attracts talented students from numerous countries. The Degree Programme in Communications Engineering still has challenges in terms of student recruitment.

In 2011, Prof. Jyri Hämäläinen was appointed as the Coordinator of the Degree Programme in Communications Engineering by the Dean of Aalto ELEC. In this position, Prof. Hämäläinen succeeds Prof. Riku Jäntti, who was appointed as Head of Department. The new Deputy Head of Department, Prof. Patric Östergård, is responsible for teaching at Comnet.

CURRICULUM DEVELOPMENT

A major issue of curriculum development during the year 2011 was participating in the Teaching Evaluation Exercise (TEE) at Aalto University. Also, the reform of the bachelor's level curricula in Aalto was started in late 2011.

The Teaching Evaluation Exercise (TEE) was started in 2010 and completed in 2011. The aim of the TEE was to promote new education culture where teachers and students give feedback in an open and constructive spirit. The TEE self-evaluation report was made in cooperation with professors, teachers and students of the degree programmes, and it was submitted in January. In April, the representatives of the international evaluation group visited ELEC and interviewed our TEE team using the self-evaluation report as a discussion framework.

The final external evaluation report was received in August, and it was presented in the all-Aalto teaching development day in September. In general, the results from the evaluation were very good and the curriculum was found to be very competitive. The report indicated, for example, the following strengths:

- The curriculum of the programme has a clear structure.
- There is a clear connection between research and education, particularly at master's level, and the programme has clear industrial relevance.
- There is pedagogical capability and strong motivation among the teachers and the programme management personnel.
- The programme is set in an international environment.

On the other hand, some problems were also identified:

- More effort is needed in planning study time allocation.

- The programme seems to have a large number of courses of only a few credits, leading to many parallel courses for the students at the end of their studies.
- There could be more diversity in teaching and assessment methods.
- The methods for obtaining feedback from students can be improved and used more frequently.

The recommended actions include, e.g., the development of student feedback methods, increased variation in teaching and assessment methods, and reduction of the number of small courses. In addition, the inflexible module system was criticized and it was recommended that the funding mechanisms for education be clarified. The ongoing curriculum reform will deal with the identified problems and take into account the recommendations.

The TEE process was arduous and created a lot of work overhead. Yet, it was found very useful since it provided an opportunity to go through several aspects of the curriculum in detail. The evaluation results were also well in line with our own findings and thus, the TEE process gave good support for the curriculum reform that was started in 2011. In the first phase of this reform, the bachelor's level curricula in Aalto will be rebuilt and the number of education areas will be decreased. By 2013, there will be one bachelor's level degree programme in ELEC that contains three education areas, namely:

- Electrical Engineering
- Automation and Information Technology
- Bioinformation Technology

The programme will be divided into the following blocks: Basic Studies (70cr) that are common in the whole school, Major (60cr) that is related to education area, Minor (25cr) and Elective Studies (25cr). The goal is to make the structure of the bachelor's level curriculum simpler and hence promote student mobility in Aalto. The reconstruction of the degree programmes will be completed in 2012.

INTERNATIONAL PROGRAMMES

A majority of the courses given by the department are lectured in English. The Master's Programme in Communications Engineering is the oldest international master's level degree programme at Aalto (formerly, TKK) and has been running since 1999, while the International Master's Programme in Communications Ecosystem, launched in fall 2010, is one of the newest. In the year 2011, the number of first-choice applicants decreased about 24% from 2010, being still approximately at the same level as in 2009. However, the enrolment of the elected international students to the two programmes in 2011 was 48 (38 in 2010), which was close to the target level.

Due to the programme, we get many very good students. International graduations constitute a significant portion of the total number of graduations, and many research assistants and PhD students in Comnet come from the Master's Programme. To conclude, currently the intake of native and international students is almost equal, while the number of international applicants to master's level programmes annually clearly surpasses the number of native applicants to the full 5-year degree programme.

The department has also been active in launching dual-degree programmes with the international partner universities of Aalto. The following dual-degree programmes are currently active:

- “Dual degree in networks and services” with Telecom & Management SudParis, France
- “Dual degree in wireless communications” with Royal Institute of Technology (KTH), Sweden
- “Dual degree in communications engineering” with networking or radio focus with Instituto Superior Técnico (IST), Portugal

It is estimated that the proportion of international graduates at the master’s level will approximately double from 15…20% to 30…50% in the next couple of years.

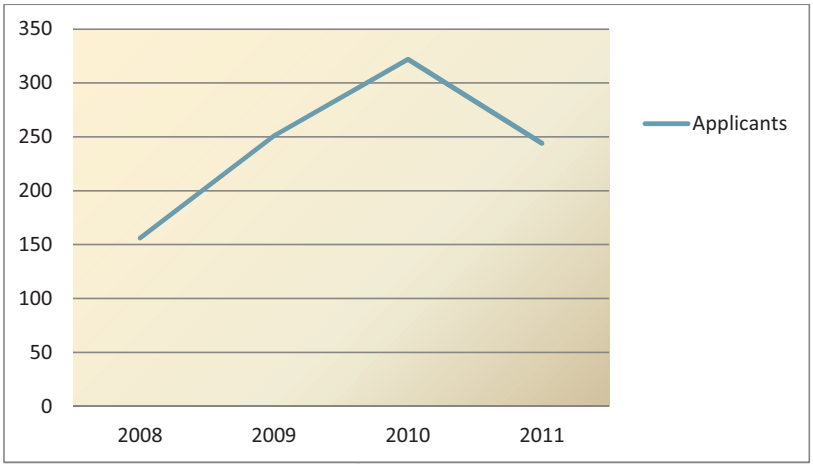

Figure 5: The number of first-choice applicants into International Master´s Programmes on Communication Engineering & Communications Ecosystem

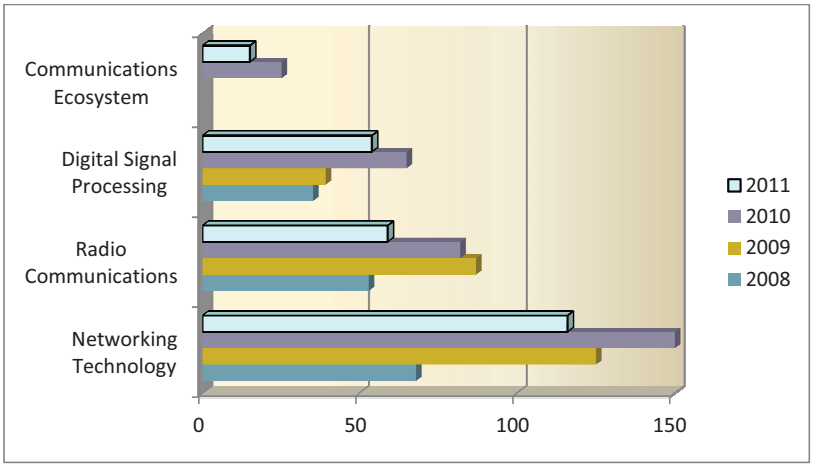

Figure 6: The number of first-choice applicants into international programmes per major

COURSES IN 2011

S-38.1105	Principles in Communication Engineering (Tietoliikennetekniikan perusteet)
S-38.1146	Introduction to Performance Analysis
S-38.1203	Networking Technology, project course (Tietoverkkotekniikan projektityö)
S-38.2121	Routing in Communication Networks
S-38.2131	Networking Technology, laboratory course A (Tietoverkkotekniikan laboratoriokurssi A)
S-38.2188	Communication Networks
S-38.3001	Telecommunications Forum P
S-38.3041	Operator Business P
S-38.3042	Seminar on Networking Business P
S-38.3046	Value Network Design for Internet
S-38.3061	Communications Ecosystem Analysis P
S-38.3062	Modelling Human Behaviour P
S-38.3115	Signalling Protocols
S-38.3120	Seminar on Communications and Networking
S-38.3133	Networking Technology, laboratory course B (Tietoverkkotekniikan laboratoriokurssi B)
S-38.3134	Networking Technology, laboratory course C (Tietoverkkotekniikan laboratoriokurssi C)
S-38.3138	Networking Technology, special assignment (Tietoverkkotekniikan erikoistyö)
S-38.3141	Teletraffic Theory P
S-38.3143	Queueing Theory P
S-38.3148	Simulation of Data Networks
S-38.3152	Networked Multimedia Protocols and Services (NMPS)
S-38.3153	Security of Communication Protocols (Tietoliikenteen tietoturva)
S-38.3156	Delay-tolerant Networking (DTN)
S-38.3159	Protocol Design P
S-38.3165	Switching Technology
S-38.3184	Network Traffic Measurements and Analysis P
S-38.3191	Network Service Provisioning P
S-38.3194	Wireless Networks
S-38.3195	Exercise Course for Network Service Provisioning P (Verkkopalvelujen tuotannon harjoituskurssi L)
S-38.3205	Individual Course on Networking Technology (Tietoverkkotekniikan yksilöllinen kurssi)
S-38.3215	Special Course on Networking Technology P (Tietoverkkotekniikan erikoiskurssi L)
S-38.3310	Thesis Seminar on Networking Technology (Tietoverkkotekniikan diplomityöseminaari)
S-38.3455	Challenged Networks P
S-38.3600	UNIX Application Programming
S-38.3610	Network Programming
S-38.4043	Postgraduate Seminar in Network Economics P
S-38.4050	Postgraduate Seminar in Communications and Networking Technology P
S-72.1010	Orientation Course for Studies in Communications Engineering (Johdatus tietoliikennetekniikan opiskeluun)
S-72.1110	Signals and Systems (Signaalit ja järjestelmät)
S-72.1110	Signals and Systems (Summer course 2011) (Signaalit ja järjestelmät)
S-72.1130	Telecommunication Systems
S-72.1140	Transmission Methods in Communication Systems
S-72.2205	Digital Transmission Methods
S-72.2211	Mobile Communication Systems and Services
S-72.2311	Laboratory Course in Communications Engineering 1
S-72.2410	Information Theory P
S-72.2510	User-Oriented Design of Telecommunications Services
S-72.3110	Individual Studies in Communications P (Yksilöllinen tietoliikennetekniikan kurssi L)

S-72.3120 Special Project in Communications
S-72.3216 Radio Communication Systems I
S-72.3226 Radio Communication Systems II
S-72.3235 Network Access P
S-72.3251 Laboratory Course in Communications Engineering 2
S-72.3260 Radio Resource Management Methods P
S-72.3281 Advanced Transmission Methods P
S-72.3295 Broadcasting and Distribution
S-72.3310 Communication Transmission Lines
S-72.3410 Coding Methods P
S-72.3510 Product Development of Telecommunication Systems

DEGREES IN 2011

Table 4: Number of degrees at Comnet in 2009-2011

Year	2009	2010	2011
D.Sc.	4	7	8
L.Sc.	1	1	2
M.Sc.	91	144	68

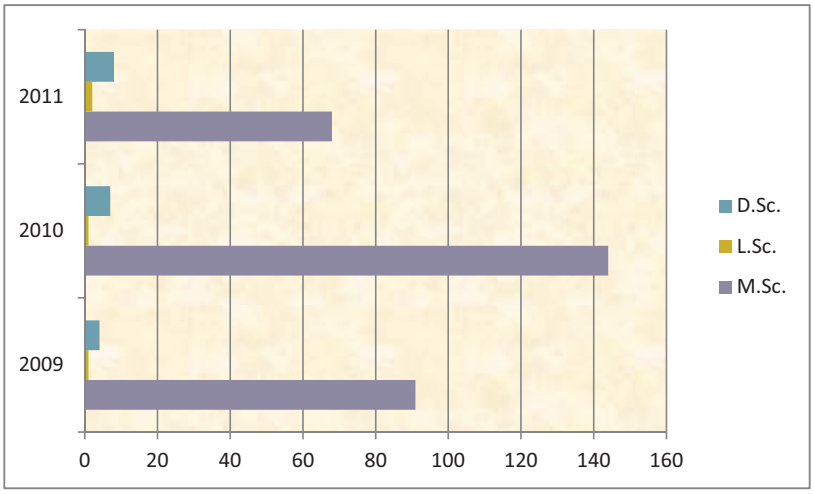

Figure 7: Degrees in 2009 -2011 as a diagram

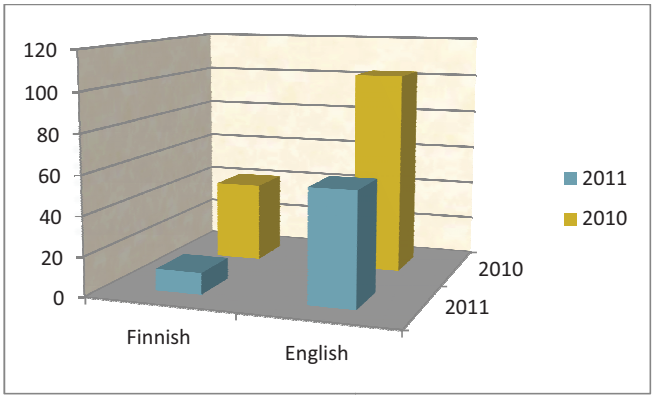

Figure 8: Languages of Master's theses 2010-2011

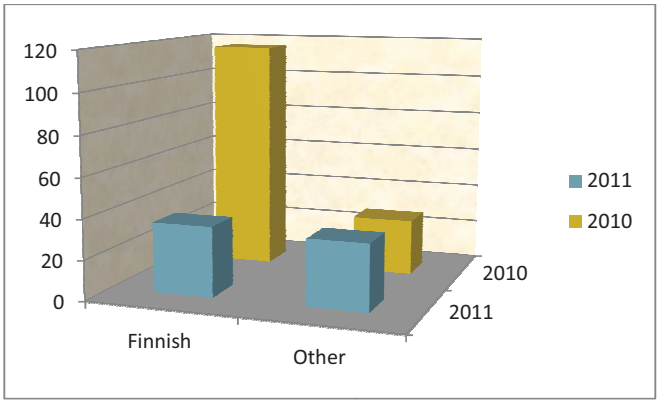

Figure 9: Finnish vs. international M.Sc. graduates 2010-2011

RESEARCH

INTRODUCTION (TO RESEARCH)

Comnet's research is multidisciplinary and broad in scope. The research continued to mature during the period. Some of the doctoral degrees are awarded to people who actually work in the industry. This is natural because of the nature of our area and the presence of world class companies with their Research units based in Finland. According to the RAE assessment by an international research panel in 2009, Comnet was strongest when measured on the societal impact of our research. During 2010 and 2011, our publications activity continued to improve in quality and overall quantity as compared to 2009. Especially, we have been able to increase the number of journal papers and doctoral thesis.

Comnet works in two large technology areas: communications and networking. These areas are often intertwined in terms of research problems. In addition, coherence is further increased by the techno-economics and human aspect's research that often collaborates in the technology projects with the technology groups and by basic research in performance analysis and in information theory. This Chapter on Comnet Research shows our work during 2011 in the two core technology areas as well as the three horizontal themes.

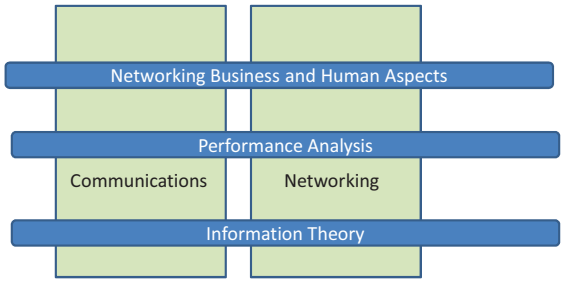

Figure 10: Comnet research areas

ADVANCED RADIO SYSTEMS PROGRAM

VISION AND MISSION

Future wireless systems will allow people to communicate with anyone, anywhere, and at any time using a range of devises and services. Wireless communication will enable self configuring intelligent home and office systems that can interact with each other and with the Internet. Also widespread wireless sensor and actuator networks are important parts of the development towards all-wireless future and Internet of Things. Our general mission is to carry out world-class research and technology development in wireless

communication technologies. Our efforts range from basic research in communications theory to applied research on practical engineering problems.

RESEARCH CHALLENGES

There is a wide span of technical challenges that we must overcome in order to make our vision possible. On our way to future we focus on the following research areas:

- **Cognitive radio and spectrum aware communications.** Remove the "hype" from cognitive radio and dynamic spectrum access discussion and replace that with clearly justified facts and quantified spectrum opportunity models. Go beyond relying on simple signal processing and detection and treat the spectrum discovery as a data fusion problem. Provisioning of commercial services based on spectrum overlay technologies will inevitably lead to situations where there are multiple competing or collaborating secondary users. In addition to the impact towards primary user performance also the secondary user performance needs to be understood and optimized as a function of secondary network load. This work also covers flexible spectrum use where the aim is to find most efficient spectrum usage approaches especially in case of multiple operators with partly or fully shared spectrum resources.
- **Wireless broadband and system optimization.** The mobile system architecture will undergo a paradigm shift from a centralized, controlled and pre-planned hierarchical system towards self-organizing, self-optimizing ad hoc operation. The driver for this development is the drastically increasing number of cells resulting from the ever increasing capacity need due to wide scale deployment of mobile Internet. Introduction of relays and small cells, such as pico and femto cells, will lead to challenging interference problems that can be tackled by local interference coordination and system optimization. Another important research challenge in future wireless broadband systems is the energy consumption. The increasing data rates and operation bandwidths are pushing up the energy needs in the network. Yet, the energy consumption can be decreased by proper system design, optimization of network operations and dynamic control of cell availability.
- **Wireless sensor systems.** We believe that wireless sensor networks are application dependent and their protocols should be jointly developed with the sensor information processing schemes. Hence, we focus on co-design of wireless sensor networking protocols, sensor data signal processing methods, data fusion methods, and in case of control applications also the control algorithms. That is, our focus is on wireless sensor systems -- not just networking. In many real-life sensing and control applications accurate timing of the sampling and control actions is essential. Also the reliability of the sensor system is a critical factor. Typically, there are trade-offs between energy consumption, accurate timing, reliability, and application performance (such as estimation accuracy, control performance etc). Hence we seek to find the right balance for each application. We focus on time and mission critical applications such as wireless automation, structural health and conditioning monitoring and situation awareness.
- **Basic research.** According to our mission we carry out both applied and basic research. The former is executed in subcontracting projects and partly in TEKES funded projects. The latter is carried out in projects funded by the Academy of Finland and TEKES, and as internal strategic research that is conducted by professors and experienced researchers.

MOST IMPORTANT PROJECTS

End-to-end Cognitive Radio Tesbed (EECRT) is a TEKES project with Nokia, Fairspectrum, DNA and Ministry of traffic and Communications. The goal of the project is to create a living lab cognitive testbed in

Otaniemi, operating on TV white space frequencies, and offering end-to-end cognitive connectivity for test persons. Building and experimenting with the testbed will create new scientific and engineering understanding on the interplay of the technical and economic boundary constraints on the design and regulation of future cognitive radio systems operating on new bands, primarily in the present TV-spectrum. The targeted understanding is of value for regulating authorities, operators, infrastructure vendors, device and hardware manufacturers, with all of these players getting a better understanding of their possible role in a cognitive radio ecosystem. The project is led by Prof. Tirkkonen. Other participants include Prof. Riku Jäntti, Prof. Jukka Manner, and Prof. Heikki Hämmäinen.

Heterogeneous and dynamic wireless access networks (HEWINETS) is a TEKES project with Ericsson and Cassidian. The project focuses on radio resource management, interference coordination, and performance analysis of heterogeneous wireless networks consisted of macro, pico, and femtocells as well as nomadic relays. The work is divided into three work packages: WP1 Moving and fixed relays (Prof. Hämäläinen and Prof. Aalto), WP2 Dynamic TDD (Prof. Jäntti and Prof. Tirkkonen), and WP3 Heterogeneous network interference coordination (Prof. Tirkkonen and Prof. Aalto).

Home Base Station: An Emerging Network Paradigm (HOMESNET). Project is part of European CELTIC HOMESNET consortium (15 organizations) and funded in Finland by TEKES, Nokia Siemens Networks and European Communications Engineering. Finnish consortium is lead by Aalto University (Professor Jyri Hämäläinen) and second Finnish research organization is VTT. Project focuses on femto base station systems that are characterized by very low costs, plug-and-play installation, low transmission power, use of existing fixed broadband (typically, digital subscriber lines) backhaul and limits access to a closed user group, such as, household members. Mass adoption HBSs will strongly influence the local area evolution.

Energy and cost efficiency for wireless access (ECEWA). This strategic TEKES Sino-Finnish collaboration project develops new cost and energy efficient solutions to future radio access networks. The use of emerging features such as femto cells, relays, and coordinated multipoint will require changes to the ways radio access networks are planned. Energy consumption of the network equipment has become increasingly important. The industry is looking ways to reduce the carbon dioxide emissions by improving the energy efficiency of the base station equipment. Energy efficiency of the networks will also impact on the way networks should be planned and operated. Saving energy also saves costs. Hence its natural to study the cost and energy efficiency jointly. The Finnish partners of the project are Aalto University, Tampere University of Technology, Ericsson, Efore, and European Communications. The project is lead by Aalto University (Professor Riku Jäntti).

Spectrum Management for Future Wireless Systems (SMAS). The objective of this three year project, funded by Academy of Finland, is threefold. First aim is to produce solid world class results to serve as a fundament of a theory of spectrum sharing. In particular, theoretical limits for the efficiency of spectrum utilization are studied. Second objective is to design general rules for spectrum sharing based on incentives of individual systems and to develop intelligent decision making methods for spectrum sharing. The third objective is to numerically determine the capacity of a network utilizing spectrum sharing. For this purpose, properties of the communication channel are modelled on the network level. The project partners are Aalto University, University of Turku and VTT. Project is lead by Aalto University.

Intelligent Structural Health Monitoring System (ISMO) is a project funded by the Multidisciplinary Institute of Digitalisation and Energy (MIDE) founded by the University.

Structural health monitoring is a new approach to provide diagnosis of the structure's condition during its life using the sensor data. An intelligent monitoring system with wireless sensor networks can provide reliable information about the structure's condition, replace visual inspections, provide ease of installation and configurability, save costs, and ultimately save people's lives. The wireless sensing and networking technologies required in intelligent monitoring systems are developed. Data mining and statistical analyses are used to extract relevant information from the sensor data for damage detection. Model-based methods are studied to estimate the location and extent of damage or predict the remaining lifetime. Possible applications include bridges, buildings, wind power turbines, ships, masts, spacecraft, forest harvesters, lift trucks, reach stackers, various crane systems, pipe systems, and amusement park rides. New business opportunities for the service sector emerge and the results can be utilized in other critical areas as well.

Networks 2020 (NETS2020). This project started in 2009 and is funded by TEKES, Nokia, Ericsson, Nokia Siemens Networks, Nethawk and Elektrobit. Research organizations are Aalto University (Professors Olav Tirkkonen and Jyri Hämäläinen) and Centre for Wireless Communications (University of Oulu). The research focus is in the future development and evolution of cellular communication systems including IMT-Advanced (IMT-A), its further evolution and its integration with other communication and data networks. The main emphasis is on evolving wireless network topologies, like relay based connections and femtocells. One of the key goals is to develop distributed algorithms performing automated network management tasks. The research is carried out in close cooperation with the best relevant universities and research institutes in China.

User-centric Design of Ubiquitous Welfare and Safety Services and Supporting Technologies for China and Finland (UBI-SERV). Project is funded by Academy of Finland and executed with Peking University (PKU). Project leader is Professor Jyri Hämäläinen. The focus is in both user centric design of services and wireless technology for ubiquitous computing (e.g. services applying networked, embedded computers) in Welfare Technology and Services (WTS). We apply a user centric design approach to pinpoint from this field the cases that fulfill research boarder conditions, focusing on senior citizens and selected public safety services, both in Chinese and Finnish service-technology-market such that academic objectives, user centric design goals and true business cases can be simultaneously investigated.

Feedback Optimization for Network-level Communication Strategies (FONCS) is a project at Aalto funded by the Academy of Finland. In the project, optimization of network-level feedback for wireless communication is addressed. The main goals are to construct a closed form analysis framework for optimizing feedback use in the physical (spatial MIMO and power control) and MAC (Channel Quality and Hybrid ARQ) layers. The framework is applied to design efficient and near-optimal feedback schemes for network-level transmission strategies. Practical and implementable feedback designs with direct relevance to the design of future spectrum-efficient wireless communication systems will be constructed. In particular, optimum feedback strategies for multiuser-MIMO (MU-MIMO), Collaborative Multipoint Transmission (CoMP) and Interference Alignment (IA) will be investigated. All of these strategies are particularly vulnerable to non-idealities in feedback, especially in the spatial domain

Robust and Secure Cognitive Radio Networks (Rosecorn) is a project funded by the Academy of Finland. The main topic investigated is coexistence of secondary users in cognitive radio networks. Secondary users, which may be associated with different cognitive networks and seek to operate in

the same frequency bands. Effective Radio Resource Management as well as security and privacy issues for cognitive networks are addressed. The project partners in Finland are Aalto University and the University of Oulu, in collaboration with Northwestern University and University of Maryland in the context of the Wireless Finland-US collaboration program.

Reliable and Real-Time Wireless Automation is a TEKES project with Department of Automation and Systems Technology, VTT, University of Vaasa, Konecranes, Metso Automaton, Wapice, Mervento, Vacon, and TK-Engineering. The RIWA project deals with reliable and real-time wireless communication and control for industrial wireless automation applications. Applying wireless technologies in industry enables flexible and cost effective automation systems. The primary goal of the project is to develop robust hardware and software components and design tools for industrial applications. The emphasis is on industrial pilots, where the research results of the projects are tested and evaluated. The pilots ensure both a tight cooperation between the research institutes and the industry partners and a guideline for researching and solving the right issues.

Interference Management for Wireless Networks Beyond Present Horizon (IMANET). The project aims at providing relevant scientific information on general interference management between network nodes that have limited capability to exchange

control information with each other. The focus in this project is to optimize the use of radio resources for a multi-antenna cellular system with varying level of coordination between the network elements. In addition, principles and methods for statistical interference management of future heterogeneous networks will be developed, analyzed and tested. Theoretical limits and guidelines for coordinated beamforming and resource allocation across different cells, relays, antennas, frequency and time dimensions with different system optimization objectives are provided. Project is joint effort between Centre for Wireless Communications (Oulu) and Aalto University. During 2011-2013 project continues under the name IMANET+.

OTHER PROJECTS

- Wireless Indoor Situation Modeling II (WISM-II), TEKES project, 2010-2012
- TIEVA-II, Finnish Defense Forces, 2010-2012
- PVTO2010 Tilannetietoisuus, Finnish Defense Forces, 2010-2011
- LTE Investigations in MIMO and Other topics (LIMO), Renesas Mobile Europe
- Machine-to-machine Self-organizing Networks, Renesas Mobile Europe
- InterMediate Cognitive Systems (IMCOS), Nokia
- Mobile Media Service Laboratory / Cognitive Connectivity, EIT

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M.Sc Maliha Jada (Network energy efficiency)

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M. Sc. Shahrukh Bin Ali (LTE-A Radio Resource Management)

M. Sc Parth Amin (Inter-Cell Interference Coordination, Self-organization)

M. Sc. Sergio Lembo (Inter-Cell Interference Coordination, feedback optimization)

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M. Sc. Renaud-Alexandre Pitaval (MIMO precoding)

M. Sc. Athul Prasad (Heterogeneous Network mobility)

M. Sc Lu Wei (Multivariate analysis of communications)

M. Sc Chia-Hao Yu (IMT-A RRM & self-organization)

M. Sc. Liang Zhou (Cognitive radio)

Alumni:

D.Sc Johanna Nieminen (Nokia Research Center)

D.Sc Mohammed Al Rawi (Ericsson)

NETWORKING RESEARCH

Professors: Raimo Kantola, Jukka Manner, and Jörg Ott

The area is addressed by three collaborating groups led by each of the professors. The **aim** is to do world class research into new networking protocols, architectures and solutions arising from broader deployment of wireless technologies, new types of applications delivered over the Internet, the scalability problems and other problems that are present in the current Internet and the technology push for scaling up the transmission speeds in the Internet.

The Networking Technology Group led by professor Kantola has concentrated on routing, switching and measurements. A particular effort has gone into Ethernetworking architectures and algorithms as well as mobile peer to peer. Also we have worked on the fundamental algorithms for packet forwarding and on the trust architecture for the Internet. The architecture is based on the principle of Best Effort *Communications* where at the customer edge we place a trust centric customer edge switch that speaks a new proposed protocol that we have called the Customer Edge Traversal protocol to other similar customer edge switches. We present our ongoing work on the architecture on the site: www.re2ee.org.

The Group for Networking Protocols, Software and Architectures led by professor Jörg Ott pursues the goal of investigating short-term and long-term architectural changes to networked systems and protocols with a focus on transport and application layer aspects. The current two core research themes are: 1) Delay-tolerant networking -inspired architectures and protocols to enable and sustain communications in challenged networking environments and their implications for future Internet design. Instances of such architectures are information-centric networking and mobile opportunistic networking. 2) Adaptive real-time communications for fixed and wireless content distribution and conversational multimedia. Essential elements in research besides modeling and simulations are prototyping applications and experimentation in test beds and the real world.

The Networking and Transport Group of Jukka Manner has developed a number of technologies to enhance data transport and network connectivity of end hosts, both mobile and fixed. The group has five research themes: 1) evolution of data transport protocols and algorithms, and multipath and multilink data transfer for both fixed and mobile nodes, 2) energy-efficiency of data centers and wireless communications with a specific focus on extending the lifetime of mobile phones, 3) Ethernet-based networking extending the IETF-driven TRILL technology (also called Routing Bridges), 4) network security with a focus on Ethernet-based networks and industrial systems and 5) a new kind of messaging platform that can connect together old analog communication systems from the 80's with modern digital high-speed and wireless technologies and provide personal, group and geographical message delivery, a kind of DTN-like system.

RESEARCH CHALLENGES

Wireless

Modeling Human-Based Networking and Communications

The is aim to further networking in which humans and their mobile devices constitute the network infrastructure – augmenting, substituting, or bypassing mobile operator infrastructure – to provide

additional communication facilities. The key challenges are in human behavior: understanding human mobility as well as patterns for sharing/accessing content and human interactions – and their interrelations. These are needed to devise suitable mobility and traffic models to for evaluating DTN protocols.

DTN Routing, Transport, and Application Protocol Design

Delay-tolerant networks may feature a number of limitations and require rethinking protocols at all layers. Most notably, such limitations include large communication latencies and intermittent or non-existing instant end-to-end paths. While quite a few applications could, in principle, still operate in such environments, their protocol design needs to change: from avoiding frequent end-to-end interactions to novel schemes for pacing traffic (congestion control) and achieving reliability to new security concepts. Routing, transport, and application functionality may require closer interaction, yet maintaining independence as much as possible.

Protocols for Lossy Environments

The goal is to develop protocols, algorithms and methods that support communication in challenged environments. These environments include the ISM band where systems and networks are built and operated without proper planning and interference control, environments for sensor networks and special radio networks like PLM. The aim is to create co-operative cross layer mechanisms that suit for particular protocol stacks and to communication middleware.

Power Consumption

Mobile network and device vendors like to advocate constantly higher speeds and the network operators seek to enhance their coverage of the country. Thus, today the consumer is in theory living great times. However, the promises the industry is making are mostly available to e.g. laptop users and devices with high processing power, and large batteries. People carrying mobile phones, the most basic and common user of mobile networks, are having problems because the new higher speed offers also consume much more energy than the previous generation. New battery technologies, and e.g. fuel cells, do not necessarily help because higher energy consumption also produces heat, which is undesirable in mobile devices being held in peoples' hands. Thus, one research area within Comnet is the design and implementation of more power efficient mobile communication, with an emphasis on the network protocols and middleware. A related ongoing topic is the energy efficiency of the other end of the data transport connection, the data centers. With the huge increase of digital services and increasing network traffic, the energy consumption of data centers and in particular the cooling and heat reuse technologies have become very beneficial topics. A related ongoing topic is the energy efficiency of the other end of the data transport connection, the data centers. With the huge increase of digital services and increasing network traffic, the energy consumption of data centers and in particular the cooling and heat reuse technologies have become very beneficial topics.

Core Networks

Research is focused on measuring and analyzing the use of networks, developing and analyzing mechanisms and architectures that are needed in networks for addressing, identification, routing, information delivery.

Ethernet Networking

The background of our work is the ongoing move from synchronous bit stream oriented transmission using PDH and SDH to asynchronous packet based transport in worldwide public networks. This move is taking place due to the tremendous growth of data traffic that overtook voice traffic in volumes soon after year 2000 and due to the lower cost of asynchronous transport. Ethernet is also a popular technology to connect thousands of servers within data centers.

The aims are 1) to develop Carrier Grade Ethernet technology for the use of Ethernet in public services packet networks and 2) to enhance the classical Ethernet technology for broader use in the Internet. Further aims are investigate the security (or lack thereof) of Ethernet and enhance Ethernetworking technology for the purpose of solving the scalability and other problems that are present in the current Internet. Achieving this aim would lead to gradual replacement of IP as the key networking protocol in the Internet.

The footprint of Ethernet is growing. A new technology is 100Gbit/s Ethernet and the use scenarios that emerge with the growing footprint. One new way to leverage Ethernet into new use cases is link aggregation. This is pursued for both access and more generic use cases.

Network Measurements Studies

Network measurements pursue the goals of understanding the characteristics and usage of both existing and future networks and evaluating performance starting from network devices and ending with large-scale networks under different conditions. The challenge in studying existing network traffic is the delicate balance between needs in-depth information and user's right to privacy. Careful anonymization and strict security procedures are the keys in protecting user's data while keeping information useful for research. Evaluating network device performance is a basic building block for reliable, high-performance networks. Finding scalability related problems in equipment and protocols require full-scale testing either in simulated or in a real network. Scalability of measurement infrastructure is ever important with the increase of link speeds. Finally, infrastructure-based measurements at certain points in the topology yield only limited insight into network operation and performance as experience by the users. Those need to be complemented by large scale measurements based upon end user equipment (for fixed and wireless/mobile networks).

Routing Algorithms

The aim is to develop algorithms for computing data structures (e.g. trees) that facilitate routing of packets with minimal cost, so that given constraints are satisfied. We seek to combine basic research on graph theory, algorithms, and computational complexity with practical heuristics and realistic requirements coming from the industry.

End-to-End Transport

Adaptive Real-Time Transport

The communication characteristics of the Internet and wireless (cellular) networks vary over time, calling for adaptive transport and application protocols. As loss patterns and congestion signals vary, different sensing and adaptation mechanisms are needed in protocol design for the respective environments, posing

particular challenges as mixed networks become commonplace and (mobile) endpoints can no longer make assumptions about their operating environment. We investigate error and rate control mechanisms for both streaming and conversational multimedia, with a focus on leveraging and enhancing the Real-time Transport Protocol (RTP). This is particularly important with multimedia communication endpoints becoming web browser-based (real-time communication in web browsers, RTCweb), a recent development in the Internet driven by the industry that will lead to an ever faster growth of multimedia traffic.

Large-Scale Multimedia Content Distribution

Moving entertainment services such as TV to the Internet (IPTV) requires the capability of large-scale content distribution – which can be either achieved by ISP-supported native IP multicast or by means of peer-to-peer overlays. Both are conceptually similar one-to-many multicast dissemination of real-time streams, requiring mechanisms for error repair and overall quality monitoring, among others. We investigate network architectures to scale to millions of receivers by applying RTP in these environments and enhancing its feedback, monitoring, and adaptive repair capabilities as needed. We also study the suitability of multi-source and multi-path communication for RTP-based media.

Multipath transport

Until very recently, most of the work on Internet transport has focused on optimizing a single path between the sender and receiver. With the increase in multi-interface mobile devices and a wealth of competing technologies to connect almost any end host and access network, we need to look much more into data transport happening in parallel over multiple paths and links. Our network research has taken a number of focus points in multipath transport, for example, efficient connectivity for multi-interface mobile devices, multipath real-time streaming, multipath TCP, and new ways to provide affordable multihoming to small and medium businesses. We have already a number of prototypes on these topics, and focus on this area is increasing year to year.

Flow and congestion control algorithms

A topic very much related to the development of the networked world is how well do the transport protocols and their algorithms work with mobile users and their devices. For example, the power consumption of a smart phone is tied to the time the radio equipment is on, not the amount of bytes transmitted. Thus, the faster we can transmit the data, the more we save energy on the mobile device. Moreover, research so far has presented a number of competing congestion control algorithms for communication over wireless links, but there is little work to make e.g. TCP-based transfer adaptive on finer scale and potentially change the used algorithms after each ACK-packet. The overall goal is to design the ultimate congestion and flow control algorithms for mobile devices typically sending small flows over a multitude of wireless technologies.

Networking Applications

Customer Edge Networking

We have studied and prototyped the principle of best effort communication where the network does its best not only for the sender like in the classical Internet but also for the receiver. Customer edge switching puts powerful policy controlled tools into the hands of the receiver and its edge device to block all unwanted traffic. A multi-homed edge tunnels all traffic through the core network to the other edge where

the inbound node can enforce its requirements on the service flow admission. We can view these edge nodes as collaborative firewalls. Customer networks can place their nodes into private address realms. The edge node offers also legacy interworking for unchanged Internet hosts. On a higher networking layer, we are modeling the concept of Internet wide trust.

Content-Based Networking

A significant portion of Internet traffic is about publishing, sharing and accessing – public and private – content. The present host-centric model of the Internet insufficiently reflects this trend, and caches and overlay architectures have been designed to improve content distribution. We investigate elements of a future content-based (or: information-centric) networking architecture, in which any router may offer generic application support functions such as caching. We have devised optimizations at the edges for content access and sharing (opportunistic cooperation between mobile nodes) and are investigating applying similar concepts to elements of the core network.

Generic Messaging

Governmental, including military, communications typically employ hardware and software that has been designed and deployed for a particular purpose. Often this hardware is rather old, and outdated in terms the current state of the art on communications. Yet, the government organizations still have to use the old hardware for years to come, while looking into upgrading the network with more up to date hardware. There is thus a tremendous need to build whole messaging systems, where new and old hardware can coexist and work together. IP is not an option in this unification because the physical connectivity and hardware are so different, and there is no unified addressing scheme that could be used end-to-end. One major research and development effort in Comnet is building a messaging platform that can merge together any communication technology available currently, or designed in the future, while making sure old legacy hardware can still be used up to it's end of life.

EXAMPLE PROJECTS

Future Internet Research Programme (ICT SHOK)

The Internet connectivity offered to end users, e.g., SMEs is somewhat two-fold: we have commodity class connectivity, e.g., home ADSL, without very high SLA guarantees, and then we have Internet access with SLA guarantees, e.g., 99,99% uptime, but with a high cost. One work item at Comnet is to design a scheme that would enable bundling multiple unguaranteed commodity class connections to form a high-speed connection with an SLA guarantee. Along the technical design, we are also investigating the business models for a virtual ISP and deployment of the technology.

Other important lines of work have concentrated on extending the lifetime of mobile phones by making efficient and intelligent use of the application protocols and wireless connectivity, and on the development of data transfer algorithms and protocols.

100GET

The Celtic 100GET project has been investigating future core network running at 100 Gbit/s links, and where the network is build over IEEE 802.3 Ethernet, or an evolution of the technology. In Finland, the subproject is composed of industry and research institutes. The focus of our work has been on two topics,

(1) understanding the scalability of legacy Ethernet and the recent IETF-driven Transparent Interconnection of Lots of Links (TRILL), and (2) extending the standard TRILL framework. This latter topic studies issues such as limiting the amount of broadcast Ethernet frames that is by nature an integral part of the technology, and making the whole network distributed, removing single points of failure and enabling efficient use of multiple routes between ingress and egress Ethernet switches across the core. Future work items in this area include suitable security models for a large Ethernet-based domain, and OAM for Ethernet networks.

MEVICO

MEVICO is an international Celtic+ project that develops technology and solutions for the future releases of 3GPP, particularly in Rel11-Rel13. We have worked on both Ethernet based transport for the access and core networks and for applying the concept of customer edge switching into mobile networks in MEVICO. More broadly, MEVICO covers relevant topics in network architecture, mobility & routing, packet transport, traffic management, network management & engineering and techno-economic aspects. The project includes both conceptual research and demo/trial system implementations. The goal is to contribute to the technical drive and leadership of the EPC network (3GPP), and thus support the European industry to maintain and extend its strong technical and market position in the mobile networks market.

NETWORK ECONOMICS

The goal of the network economics group is to improve understanding of (mobile) technology acceptance by measuring and analyzing user behavior, by studying alternative technical and industry architectures, and by evaluating the techno-economic performance of new technologies.

RESEARCH CHALLENGES

Quantitative analysis of mobile user behavior

The always-on and multipurpose nature of personal mobile devices has enabled accurate quantitative analysis of mobile user behavior. We are challenging the boundaries of complex data mining and privacy by collecting and analyzing e.g. transaction data (from mobile devices), traffic data (from routers) and demographics data (from service providers and user questionnaires). The aim is to better understand user behavior in contexts (e.g. by location and activity), social networks (virtual vs. real world) and service adoption/diffusion.

Optimal industry and technical architecture for flexible radio access

Wireless Internet access technologies are gradually enabling more flexible use of spectrum (e.g. cognitive radio) and potentially higher utilization levels of scarce spectrum. This flexibility is emerging via two separate evolution paths: licensed and unlicensed. Our challenge is to better understand the technical, regulatory and economic rules needed to optimize the use of the bottleneck radio spectrum.

Techno-economic bottlenecks of Internet scalability

The Internet architecture and protocols need to scale up radically in the coming years. Anticipation of the key architectural bottlenecks early enough is of importance. Some of these bottlenecks are techno-economic by nature and cannot be easily solved without understanding of the related economics. Our challenge is to identify these techno-economic bottlenecks and to design techno-economic solutions for eliminating them.

EXAMPLE PROJECTS

MoMIE (Modeling of Mobile Internet Ecosystem)

MoMIE (2011-2012) is a national project involving the key actors of the Finnish mobile market. Mobile usage data has been collected and analyzed in a bottom-up manner to identify the trends and patterns in the Finnish market. Theories, models and hypotheses are created in a top-down manner and linked back to the experimental usage data. The resulting increased visibility to service adoption and diffusion may help market actors in business planning.

EECRT (End-to-end Cognitive Radio Testbed)

EECRT (2011-2013) includes our techno-economic analysis part to support alignment of technical architectures with market architectures. We have used system dynamics for the top-down modeling of the radio access evolution and agent-based modeling for the bottom-up analysis of potential TV white space exploitation scenarios. One major observation is that local area application of white space looks more attractive.

Tivit Future Internet – socio-economics

As part of the national Future Internet program (2008-2012) we have studied the techno-economic scalability bottlenecks of Internet, mainly together with NSN and Ericsson. After the initial scenario planning tasks our focus moved to bottleneck analysis of core protocols such as IPv6, HIP, LISP, and multipath protocols. Promising results have been achieved using system dynamics both as a qualitative and quantitative analysis method in order to understand the complex forces of technology diffusion.

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INFORMATION THEORY

Professors: Patric Östergård

The goal of the information theory group is to solve problems in discrete mathematics that arise in coding and information theory. A variety of computational methods are used, enhanced by algebraic and combinatorial techniques. The research is mainly funded by the Academy of Finland and led by Professor Patric Östergård.

COMPUTATIONAL METHODS IN DISCRETE MATHEMATICS AND INFORMATION THEORY

The aim of the research is the study of existence and classification problems in discrete mathematics and information theory using computational methods, enhanced by algebraic and combinatorial techniques. The methods are developed in a general framework, and have been applied to numerous types of discrete structures, such as codes, designs, and graphs, just to mention a few.

The work on classifying and enumerating discrete structures has formed a continuation of earlier work that culminated in the monograph [P. Kaski and P.R.J. Östergård, Classification Algorithms for Codes and Designs, Springer, Berlin, 2006]. Along this line, we have achieved several groundbreaking results in the recent years, including a classification of the perfect binary one-errorcorrecting codes of length 15 and an enumeration of the Latin squares of order 11.

The work on classifying the perfect binary one-error-correcting codes of length 15 has been continued by classifying various other closely related codes. In particular, we have settled a longstanding open problem regarding the possibility of extending codes with certain parameters to perfect codes (in the negative). First, exceptional codes of length 12 were found, and this result was later extended to get an infinite family of exceptional codes.

Switching is a general technique for transforming a discrete structure into another with the same main parameters. There are many applications for switching, for example, switching can be used to obtain new

(nonisomorphic/inequivalent/...) structures from known ones. In this manner, through a massive computer search, we have shown that the cycle switching graph of the 11084874829 Steiner triple systems of order 19 is connected, that is, one can get from any of the structures to any other via a sequence of (cycle) switches. This essentially explains the large number of such structures. This is just one particular example of results obtained in the study of switching.

The research group has further studied and published results on difference matrices and several types of generalized Hadamard matrices; unrestricted and constant weight error-correcting codes; Hamiltonian cycles and paths in graphs; and coloring and domination problems for graphs. All these problems concern fundamental mathematical structures or properties motivated by applications in telecommunications or more generally in engineering.

Software libraries for solving various common combinatorial problems have been developed along the years. The program **libexact** solves instances of the so-called exact cover problem. This piece of software is frequently useful in the study of combinatorial structures, and forms an important complement to the Cliquer routines, also released by the group. The **libexact** and Cliquer routines were invaluable building blocks in the algorithms used to obtain several of the particular results listed above. Algorithms for various problems have also been developed in the framework of Russian doll search. Stochastic methods, in particular, tabu search - have also been considered for certain construction problems. In general, many of the computational results obtained have required very CPU-intensive computations, some of which have been distributed over extensive computer networks. For this purpose, an 80-core computer cluster was acquired in 2010; this computing environment has brought some relief to the constant need for more computing power.

Researcher training plays a central role in the group. Esa Seuranen defended his doctoral thesis in November 2011, and several more defenses are expected in the near future. The group is collaborating extensively and internationally.

The work of the group has received international recognition and the group leader is a frequent plenary speaker at international meetings. He is also a co-Editor-in-Chief for the Journal of Combinatorial Designs.

CORE GROUP

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PERFORMANCE ANALYSIS

Professors: Samuli Aalto (pro tem) and Jorma Virtamo (emeritus)

Performance analysis group focuses on the mathematical modeling, performance analysis and optimization of modern communications systems and networks from the traffic point of view. The mathematical methods applied include stochastic modeling, queueing theory, and teletraffic theory. In addition, scheduling theory, optimization theory, discrete-event simulation, and various numerical methods play a central role. We strive both for new theoretical breakthroughs in the area of queueing and teletraffic theory and an insightful analysis of modern communications systems, networks, and applications.

RESEARCH CHALLENGES

The work done by the group is challenged by a multidisciplinary race after ever increasing technological complexity of communications systems as well as methodological innovations in related applied mathematics. The focus areas are as follows:

Flow level performance analysis of elastic data traffic

Bandwidth sharing networks are used to model the performance of data networks loaded with elastic traffic. The group has contributed to the extension of the concept of Balanced Fairness, which allows analytical studies of bandwidth sharing networks at the flow level. In addition, the group has developed and analyzed flow level models for elastic data traffic in the context of wireless cellular networks.

Optimal control of queueing systems based on age and size information

Recent years have witnessed a resurgence of the scheduling theory. New applications from modern computer and communications systems have played an important role. The group has been active in this resurgence of scheduling. We have found new fundamental results for age-based scheduling in the classical M/G/1 queueing context under highly-varying workloads. Moreover, the group has participated in extending the system models beyond the M/G/1 queue by considering age and size-based scheduling problems in wireless cellular networks and bandwidth sharing networks. The group has also participated in the development of near-optimal size-aware dispatching policies for parallel queueing systems. As a new line of research, we have considered optimal control problems of queueing systems from the energy efficiency point of view.

Performance analysis of multi-hop wireless networks

The fundamental capacity limits of wireless multi-hop networks can be elegantly analyzed in the limit of so-called dense networks. The capacity maximization separates into two distinct problems: optimal load balancing and maximum forwarding capacity. For the optimal load balancing problem innovative applications of concepts from physics have been applied. Analysis of the forwarding has focused recently, e.g., on the impact of different interference models on the forwarding capacity.

PROJECTS

Euro-NF (Network of the Future)

Euro-NF (2008-2012) is an EC FP7 Network of Excellence (NoE). It is formed by 35 European institutions (from the academia and industry) and coordinated by Institut Telecom (from France). Within the project, we have international collaboration in the area of mathematical modeling and performance analysis of future networks.

ICT SHOK FI (Future Internet)

The group participates in the Future Internet Programme, which started in 2008. Our focus has been on the mathematical modeling and performance analysis of peer-to-peer (P2P) networks. In collaboration with Prof. Sasu Tarkoma's group in HIIT, we have developed and analyzed new performance models for P2P video-on-demand systems. We have also developed mathematical models for analyzing the feasibility of floating content, an ephemeral content sharing service based purely on opportunistic contacts between the peers. This has been joint work with Prof. Jörg Ott's group in COMNET and Prof. Jussi Kangasharju's group in University of Helsinki.

HEWINETS (Dynamic Heterogeneous Wireless Access Networks)

The group is responsible for the national HEWINETS project (2011-2013) funded by TEKES and industry. This is a joint project with the COMNET research groups of Prof. Jyri Hämäläinen, Prof. Riku Jäntti, and Prof. Olav Tirkkonen. The focus of the project is to analyze the key issues affecting the radio resource management of heterogeneous wireless access networks relevant in LTE systems and beyond. In the first year, we have modeled and analyzed the flow-level performance of elastic data traffic in a cellular system operating under dynamic TDD.

CORE GROUP

Prof. (pro tem) Samuli Aalto, group leader

Prof. (emeritus) Jorma Virtamo

Dr. Pasi Lassila

Dr. Aleksi Penttinen

Dr. Tuomas Tirronen

M.Sc. Jarno Nousiainen

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APPENDICES

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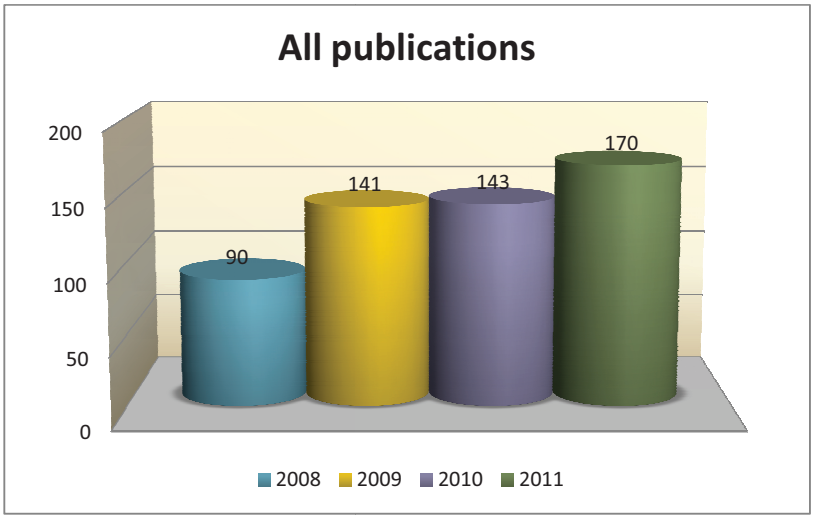

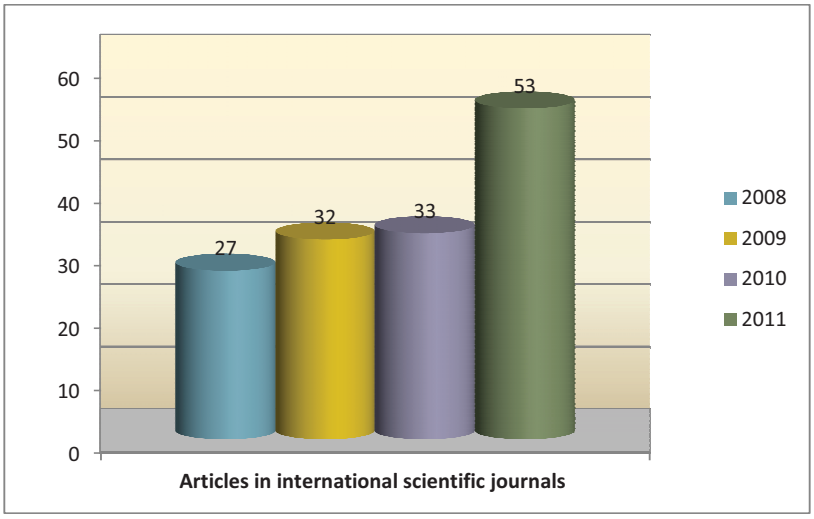

ABSTRACTS OF DOCTORAL THESES 2011

Gonzalo Camarillo: A Service-enabling Framework for the Session Initiation Protocol (SIP)

Supervisor: Prof. Raimo Kantola

In this dissertation, we propose a framework to provide multimedia communication services. Our proposed framework is based on SIP (Session Initiation Protocol) and has four fundamental properties: it is available, secure, high performing, and oriented to innovations. The framework is not an architecture with a rigid structure. Instead, the framework is a toolkit made up of a set of tools that can be combined in different ways. The combination of these tools provides applications and services with functionality needed to implement a wide variety of multimedia communication services. Applications and services built on top of the framework use different tools within the toolkit in order to provide their desired overall functionality.

The functionality provided by the framework includes a number of primitives to be used by applications and services. These primitives mostly relate to multiparty communications and include floor control. The framework also offers support functions that relate to PSTN (Public Switched Telephony Network) interworking, policy control, and consent-based communications. Additionally, the framework contains functions that relate to signalling transport, multihoming, mobility, security, and NAT (Network Address Translation) traversal. The framework also allows building overlay networks when a SIP network infrastructure is not available.

In order to test and refine the ideas presented in this dissertation, we have implemented most of them in proof-of-concept prototypes. We have used experiments and simulations to validate our assumptions and obtain new insights.

Antero Kivi: Diffusion of Mobile Internet Services

Supervisor: Prof. Heikki Hämmäinen

Mobile Internet is an outcome of the merging of two significant domains of technological innovation over recent years: mobile/wireless and the Internet. This merging will lead to new forms of end-user behaviour and also provide business opportunities for companies from the converging telecommunications, IT/Internet, and media industries. The diffusion of technological innovations is widely discussed in the literature. However, applications of the diffusion theory to mobile services have mostly concentrated on mobile telephony, and considered this diffusion to result from end-user adoption decisions that are made independently of other innovations. In contrast, the thesis of this dissertation is that the diffusion of mobile Internet services as systemic technological innovations depends on a cluster of separate but interrelated technology components that diffuse interdependently due to both demand-driven adoption and supply-driven dissemination.

This research was conducted using quantitative research data on mobile handsets and services collected from Finland during the years 2005-2009. The diffusion of mobile Internet services was found to depend on the generic technology components of mobile services: devices, applications, networks, and content. These

components form an interrelated cluster of technologies. Consequently, direct market actor influence over a specific technology component has indirect effects on the other generic components, and, thereby, also influences the diffusion of mobile Internet services.

This dissertation contributes to the fields of innovation diffusion and mobile services research. Firstly, a general approach for planning and forecasting technology product evolution and new product feature diffusion was developed by isolating the previously unexplored phenomenon of product feature dissemination and linking it to the known phenomena of product category diffusion and product unit replacement. Secondly, observations on the diffusion of systemic technological innovations were made in the context of mobile Internet services related to component technology interdependence, market actor dissemination efforts, and end-user assimilation gaps. Thirdly, the fundamental differences of alternative methods to measure mobile service usage as well as the data provided by them were identified, and a holistic framework for analysing the usage of mobile services was developed. Fourthly, novel research methods and data were utilised.

Johanna Nieminen: Adaptive Scheduling in Cellular Access, Wireless Mesh and IP Networks

Supervisor: Prof. Riku Jäntti

Networking scenarios in the future will be complex and will include fixed networks and hybrid Fourth Generation (4G) networks, consisting of both infrastructure-based and infrastructureless, wireless parts. In such scenarios, adaptive provisioning and management of network resources becomes of critical importance. Adaptive mechanisms are desirable since they enable a self-configurable network that is able to adjust itself to varying traffic and channel conditions. The operation of adaptive mechanisms is heavily based on measurements. The aim of this thesis is to investigate how measurement based, adaptive packet scheduling algorithms can be utilized in different networking environments.

The first part of this thesis is a proposal for a new delay-based scheduling algorithm, known as Delay-Bounded Hybrid Proportional Delay (DBHPD), for delay adaptive provisioning in DiffServ-based fixed IP networks. This DBHPD algorithm is thoroughly evaluated by ns2-simulations and measurements in a FreeBSD prototype router network. It is shown that DBHPD results in considerably more controllable differentiation than basic static bandwidth sharing algorithms. The prototype router measurements also prove that a DBHPD algorithm can be easily implemented in practice, causing less processing overheads than a well known CBQ algorithm.

The second part of this thesis discusses specific scheduling requirements set by hybrid 4G networking scenarios. Firstly, methods for joint scheduling and transmit beamforming in 3.9G or 4G networks are described and quantitatively analyzed using statistical methods. The analysis reveals that the combined gain of channel-adaptive scheduling and transmit beamforming is substantial and that an On-off strategy can achieve the performance of an ideal Max SNR strategy if the feedback threshold is optimized. Finally, a novel cross-layer energy-adaptive scheduling and queue management framework EAED (Energy Aware Early Detection), for preserving delay bounds and minimizing energy consumption in WLAN mesh networks, is proposed and evaluated with simulations. The simulations show that our scheme can save considerable amounts of transmission energy without violating application level QoS requirements when traffic load and distances are reasonable.

Jyrki T. J. Penttinen: The Planning and Optimisation of DVB-H Radio Network

Supervisor: Prof. Sven-Gustav Häggman

In the DVB-H (Digital Video Broadcasting – Handheld) radio network planning, there are details that lack final consensus in the scientific field. The aim of this doctoral dissertation is to investigate advanced DVB-H radio network planning and optimisation. This dissertation presents the results of measurement techniques, network coverage and quality estimation, technological and economical optimisation, as well as error correction and single frequency network performance. The outcome includes proposed DVB-H radio network planning and optimisation methods that can be applied to the further investigation of detailed parameters in the radio link budget. There are also case studies that show the functionality of the presented methods with typical performance values.

Based on comparative investigations, a process chart was created for DVB-H radio network planning and optimisation. The process blocks can be applied in a typical DVB-H network deployment, for the initial high-level phase as well as in the detailed network planning and optimisation phase. Using this process, the most relevant items were selected for in-depth studies. The investigations are presented in the annexed publications. The reminder was revised by comparative literature studies. The structure of the thesis follows the designed process charts.

The main focus of this dissertation is the development of DVB-H radio network planning methodologies. One of the goals was to investigate the radio interface measurements, their post-processing and analysis. This can provide a guide to the selection of the appropriate values as a function of the radio channel type. An additional goal is the controlled management of over-sized single frequency network areas through the balancing of elevated SFN interference levels and related SFN gains. The development of a radio path loss simulator is the basis for these studies. The case results are presented as a function of the relevant radio parameter values, transmitter power levels and site antenna heights, both in theoretical and realistic network layouts. In addition to these topics, this document also investigates selected electro-magnetic compatibility, human exposure safety zones and radio coverage estimations. Also the balancing of technical radio parameters and network costs in order to complete the planning process steps is covered.

Mikko Pitkänen: Data Availability in Challenging Networking Environments in Presence of Failures

Supervisor: Prof. Jörg Ott

This Doctoral thesis presents research on improving data availability in challenging networking environments where failures frequently occur. The thesis discusses the data retrieval and transfer mechanisms in challenging networks such as the Grid and the delay-tolerant networking (DTN). The Grid concept has gained adaptation as a solution to high-performance computing challenges that are faced in international research collaborations. Challenging networking is a novel research area in communications.

The first part of the thesis introduces the challenges of data availability in environment where resources are scarce. The focus is especially on the challenges faced in the Grid and in the challenging networking scenarios. A literature overview is given to explain the most important research findings and the state of the standardization work in the field.

The experimental part of the thesis consists of eight scientific publications and explains how they contribute to research in the field. Focus in on explaining how data transfer mechanisms have been improved from the application and networking layer points of views. Experimental methods for the Grid scenarios comprise of running a newly developed storage application on the existing research infrastructure. A network simulator is extended for the experimentation with challenging networking mechanisms in a network formed by mobile users. The simulator enables to investigate network behavior with a large number of nodes, and with conditions that are difficult to re-instantiate.

As a result, recommendations are given for data retrieval and transfer design for the Grid and mobile networks. These recommendations can guide both system architects and application developers in their work. In the case of the Grid research, the results give first indications on the applicability of the erasure correcting codes for data storage and retrieval with the existing Grid data storage tools. In the case of the challenging networks, the results show how an application-aware communication approach can be used to improve data retrieval and communications. Recommendations are presented to enable efficient transfer and management of data items that are large compared to available resources.

Kalle Ruttik: Secondary spectrum usage in TV white space

Supervisor: Prof. Riku Jäntti

Currently, the use of TV frequencies is exclusively license based with the area not covered by licensed TV transmitters being known as TV white space. In TV white space, the spectrum can be reused by a secondary user. This thesis studies how the TV white space can be used by a cellular system. The study addresses the problems of how the access to the spectrum is arranged, how the spectrum usage is constrained and how much capacity a secondary system will have.

The access to TV white space can be arranged by using spectrum sensing or a geolocation database. This spectrum sensing relies on the performance of the signal detection algorithm. The detector has to operate in a fading environment where it should identify very low signal levels. In this thesis, the detector performance in a slow and fast fading environment is modeled. The model indicates that for a sufficiently long measurement time the impact of the fast fading can be averaged out. Unfortunately, simple single antenna-based detectors are not able to operate at a low enough signal-to-noise level. We propose a novel multi antenna-based detection algorithm that is specially designed to operate in a fading environment. TV white space is characterized by the amount of spectrum available for secondary usage. Because of the signal detection errors, a system using the sensing-based access is not able to use the entire available spectrum. This dissertation provides a method for estimating the spectrum utilization efficiency. The method illustrates how the detection error level affects the amount of available spectrum.

One of the central questions studied in this thesis is how to describe the interference generated by the secondary transmitters. In the conventional model, the interference is computed as the sum of the interfering powers from individual transmitters. An alternative approach, pursued here, is to characterize the transmitter by its transmission power density per area. With such a model, the interference computation is done by integrating over the secondary system deployment area. The proposed method simplifies the interference estimation process.

In data communication systems the spectrum attractiveness depends on the data rate the system can provide. Within the scope of this work, the achievable data rate is computed for a cellular system. Such computation is described as an optimization problem. The solution to this problem is found by searching for the optimal power allocation among the cochannels and the adjacent channels of a nearby TV transmitter.

Esa Seuranen: Computational Methods in Codes and Games

Supervisor: Prof. Patric Östergård

This dissertation discusses exhaustive search algorithms and heuristic search methods in combinatorial optimization, including combinatorial games.

In this work unidirectional covering codes are introduced and some theoretical foundations for them are laid. Exhaustive search is used to construct asymmetric covering codes, unidirectional covering codes and multiple coverings with given parameters—or to show that no such codes exist. Integer programming formulations, bounds on maximal coverages of partial codes and code isomorphisms are used to prune the search space.

Tabu search is used to construct asymmetric and unidirectional covering codes—with several record-breaking codes for the former. A new definition for neighborhood is derived.

The traditional board game of go and computer go results are reviewed. The concept of entropy is introduced into the game context as a metric for complexity and for relevance (of features—like distance to the previous move). Experimental results and questionnaire studies are presented to support the use of entropy.

Mikko Särelä: BloomCasting for Publish/Subscribe Networks

Supervisor: Prof. Jörg Ott

Publish/subscribe has been proposed as a way of addressing information as the primary named entity in the network. In this thesis, we develop and explore a network architecture based on publish/subscribe primitives, based on our work on PSIRP project. Our work is divided into two areas: rendezvous and Bloomcasting, i.e. fast Bloom filter-based forwarding architecture for source-specific multicast. Taken together these are combined as a publish/subscribe architecture, where publisher and subscriber matching is done by the rendezvous and Bloom filter-based forwarding fabric is used for multicasting the published content.

Our work on the inter-domain rendezvous shows that a combination of policy routing at edges and an overlay based on hierarchical distributed hash tables can overcome problems related to incremental deployment while keeping the stretch of queries small and that it can solve some policy related problems that arise from using distributed hash tables in inter-domain setting.

Bloom filters can cause false positives. We show that false positives can cause network anomalies, when Bloom filters are used for packet forwarding. We found three such anomalies: packet storms, packet loops, and flow duplication. They can severely disrupt the network infrastructure and be used for denial-of-service attacks against the network or target services. These security and reliability problems can be solved by using the combination of three techniques. Cryptographically computed edge pair-labels ensure that an attacker cannot construct Bloom filter-based path identifiers for chosen path. Varying the Bloom filter parameters locally at each router prevents packet storms and using bit permutations on the Bloom filter locally at each router prevent accidental and malicious loops and flow duplications.

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THESES

Author: Topic	**Supervisor**
Aaltonen, Atte: Usability Inspection for Customer Selfcare: Case Study for a Teleoperator	Timo Korhonen
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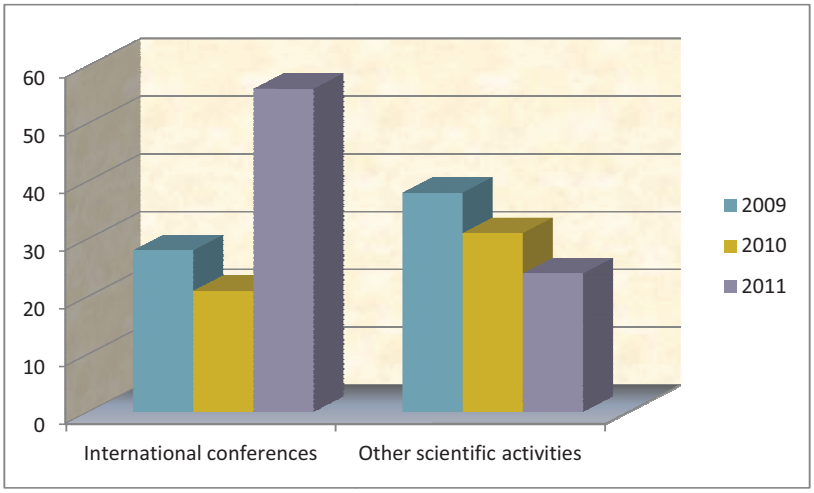
Ekberg, Jan-Erik: Efficient Baseband Security	Raimo Kantola
Peltola, Matti: Evolution of Public Safety and Security Mobile Networks	Heikki Hämmäinen

ACTIVITIES



ACADEMIC ACTIVITIES

Heikki Hämmäinen

- Opponent to Jan Markendahl, KTH Royal Institute of Technology

Jyri Hämäläinen

- Opponent to Mikael Fallgren, KTH Royal Institute of Technology

Raimo Kantola

- External Examiner of Doctoral Thesis, Tapio Saarelainen, National Defense University

Timo Korhonen

- Opponent to Jiehan Zhou, University of Oulu

Jukka Manner

- Opponent to Jukka Mäkelä, University of Jyväskylä

Patric Östergård

- External Examiner of Doctoral Thesis, Johannes Zwanzger, Universität Bayreuth

CHAIRMANSHIPS AT THE CONFERENCES IN 2011

Heikki Hämmäinen

- Conference of Telecommunication, Media and Internet Techno-Economics (CTTE), Berlin, Germany

Raimo Kantola

- The 6th International Conference on Frontier of Computer Science and Technology (FCST-11) in conjuction with IEEE TrustCom 2011, Changsha, China
- The 2011 IEEE International Workshop on Trust and Identity in Mobile Internet, Computing and Communications (IEEE TrustID 2011) in conjuction with IEEE TrustCom 2011, Changsha, China

Timo Kiravuo

- The 10th IEEE International Conference on Trust, Security and Privacy in Computing and Communications (IEEE TrustCom 2011), Changsha, China

Pasi Lassila

- Fundamentals of Future Networking Workshop, Espoo, Finland

Jörg Ott

- Principles, Systems and Applications of IP Telecommunications (IPTComm 2011), Chicago, USA

Aleksi Penttinen

- 30th IEEE International Performance Computing and Communications Conference IPCCC 2011, Orlando, Florida, USA

Zheng Yan

- Trust on Cloud Computing in The 10th IEEE International Conference on Trust, Security and Privacy in Computing and Communications (IEEE TrustCom 2011), Changsha, China
- KeyNote of TrustID 2011 in The 10th IEEE International Conference on Trust, Security and Privacy in Computing and Communications (IEEE TrustCom 2011), Changsha, China

Patric Östergård

- 35th Australasian Conference on Combinatorial Mathematics & Combinatorial Computing, Melbourne, Australia

VISITS ABROAD IN 2011

Somaya Arianfar

- University of California, Berkeley, 2 months

Thomas Casey

- Kungliga Tekniska högskolan, Sweden, 2 weeks

Visa Holopainen

- Grafenwoehr, Germany, 2 weeks

Mika Husso

- Universitat Politècnica de Catalunyaan (UPC), Spain, 2 months

Kalevi Kilkki

- European Commission, Belgium, 3 weeks

Marko Luoma

- Grafenwoehr, Germany, 2 weeks

Edward Mutafungwa

- Tanzania, 3 weeks

Lu Wei

- Hong Kong University of Science and Technology, China, 4 months

Zheng Yan

- XiDian University, China, 1 month

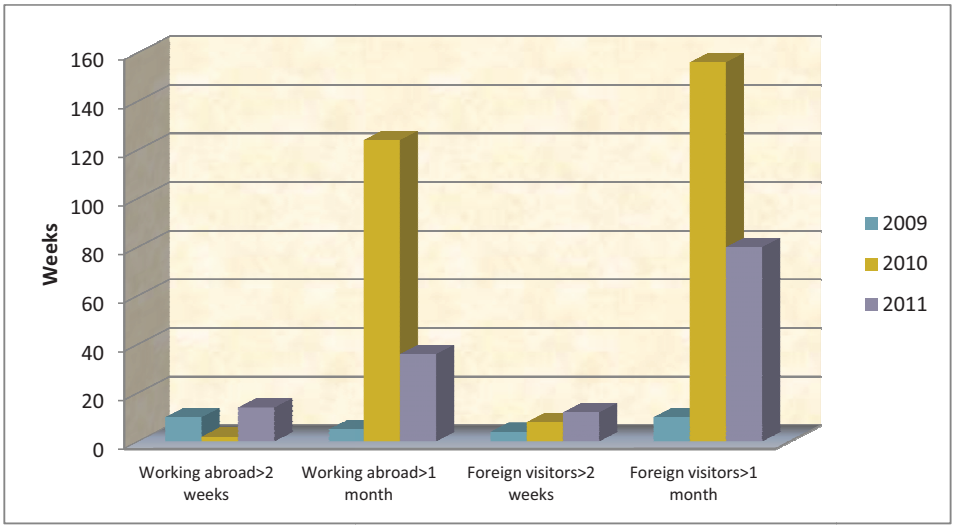
Patric Östergård

- Universität Rostock and Universität Bayreuth, 2 weeks

FOREIGN VISITORS IN 2011

- Azcorra, Arturo from Carlos III University, Spain
- Bhamri, Ankit from EURECOM, France
- Bohora, Vivek Ashok from Nanyang Technological University, Singapore
- Bou Saleh, Abdallah from NSN, Germany

- Bulakci, Ömer from NSN, Germany
- Castillo-Pérez, Sergio from Universitat Autonoma de Barcelona, Spain
- Crowcroft, Jon from University of Cambridge, Great Britain
- Dharmawansa, Prathapasinghe from The Hong Kong University of Science and Technology, Hong Kong
- Huang, Xueqing from Beijing University of Posts and Telecommunications, China
- Kim, Seong-Lyun from Yonsei University, Korea
- Komnios, Ioannis from Democritus University of Thrace, Greece
- Luo, Bing from Beijing University of Posts and Telecommunications, China
- Mascolo, Cecilia from University of Cambridge, Great Britain
- Masri, Ahmed from Politecnico di Torino, Italy
- Mumey, Brendan from Montana State University, USA
- Mähönen, Petri from RWTH Aachen University, Germany
- Odlyzko, Andrew from University of Minnesota, USA
- Solov´eva, Faina from Sobolev Institute of Mathematics, Russia
- Stiller, Burkhard from University of Zürich, Switzerland
- Varadharajan, Sridhar from Sasken Communication Technologies, India
- Vitiello, Federica from NSN, Germany
- Waldburger, Martin from University of Zürich, Switzerland
- Zander, Jens from Kungliga Tekniska högskolan, Sweden
- Zhao, Yuping from Peking University, China



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